Multimodal Sensing and Intelligent Fusion for Remote Dementia Care and Support

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ABSTRACT

A comprehensive multi-sensor monitoring and feedback system is presented, designed to support independent living for elderly people with dementia or other conditions, and provide decision support for their formal and informal caregivers. This solution goes significantly beyond existing monitoring and assisted living approaches, which operate with a simple set of sensors and measurements, as it integrates a very heterogeneous set of sensing modalities and technologies, including video, audio analysis, in addition to physiological, environmental and other measurements. Semantic web technologies are used in for the intelligent integration and feedback of the sensor analysis results, in line with user requirements, dictated by clinicians. This results in relevant feedback and decision support, which is communicated to the end users via appropriately designed user interfaces. A variety of clinical scenarios and environments are supported, from short-duration testing in hospital environments to long-term daily life monitoring and support at home, for independent living.

Categories and Subject Descriptors

[**Human-centered Computing**]: Ubiquitous and Mobile ComputingAmbient Intelligence; [**Applied Computing**]: Healthcare Information Systems; [**Computing Methodologies**]: Knowledge Representation and Reasoning

Keywords

ambient assisted living; sensors; semantic web; ontologies; reasoning; context-awareness; dementia;

1. INTRODUCTION

The ageing population of the world is leading to an increase in chronic conditions associated with old age, such as dementia. Their social, economical and personal burden is enormous, as they can prove debilitating for individuals, who can no longer live independently. Assisted living solutions are being designed to help, providing discreet but relevant monitoring and decision support to elderly people living alone and their caregivers, who can remotely obtain a picture of the person's condition, so as to provide personalized, effective care.

This work presents the Dem@Care system, a comprehensive, multi-sensor monitoring solution for individuals with dementia, deploying a great variety of sensors to monitor the environment, their physiological status, overall health and lifestyle aspects, including sleep, levels of activity, sociability, mood. The heterogeneous sensor data is integrated in an intelligent manner, resulting in a comprehensive picture of the person's current status and its evolution over time, allowing caregivers to determine the best care approach in each case. Dem@Care utilizes the DemaWare2 framework for interoperability in an AAL environment, described in detail in [11]. This system has been tested with success in real world conditions in Ireland, France, Sweden and Greece, in hospital and home environments, addressing the user needs and ethical requirements of each setup. In the future this solution can be expanded with State of the Art (SoA) sensors and analysis, for timely, accurate outcomes leading to relevant feedback and optimal care.

Each sensing modality is analyzed separately, and their results are integrated in a semantically meaningful manner, in line with user requirements dictated by healthcare professionals, the informal caregivers, as well as the patients themselves. The outcomes can range from reminders (e.g. if a person has a doctor's appointment) to more sophisticated advice on lifestyle changes, suggested based on the multi-sensor measurements, medical expertise and that specific person's profile. The technologies used span smarthome monitoring sensors, such as temperature, humidity, motion sensors, to wearables for monitoring the person's physiological status. Additionally, new modalities are deployed - and integrated for the first time - in such a comprehensive manner. Namely, audio recordings of speech are analyzed to detect early signs of potentially pathological changes, video monitoring gives a clear picture of lifestyle and changes in it, particularly concerning the ability to carry out activities of daily living, and sleep is monitored in a passive, unobtrusive manner, as it is a rich source of information for an individual's health status.

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2. RELATED WORK

Recent years have seen a great upsurge in the development of Ambient intelligence and Ambient Assisted Living (AAL) frameworks, which have already been deployed in smart homes for health and lifestyle monitoring, safety and other applications. The sensor modalities chosen are tailored to the end user needs in each case, with the initial solutions on the market today[1] mostly focusing on environmental and security-related sensing (light, temperature, humidity, open/close doors/window etc) [9]. Additionally, most existing solutions monitor only one domain, using a single or a few devices. Some applications are geared towards wandering behavior prevention with geolocation devices, assessment of levels of physical activity, sleep, daily activities [8], [4]. A sensor network deployed in real world nursing homes in Taiwan [3] is used to continuously monitor vital signs of the inhabitants. However, that system has limited interoperability, as it cannot fuse additional modalities like environmental or sleep sensors. A platform [10] has been developed in France for remote monitoring and assistance of elderly, however multiple sensor results are simply combined, rather than integrated in an intelligent manner that takes into account expert knowledge (from clinicians), context, and each end user's particular needs. Other solutions, like Ubisense[2], only examine personal activity levels and other physiological measurements, but disregard the environment and context in general.

Numerous research efforts are also taking place to involve robots in assisted living environments[3], however they are often costly and impractical, so they still need time to become widely accepted and adopted on a large scale. Robots will indeed form an integral part of assisted living solutions in the future [5], [6], [7] but are beyond the scope of this work, in which we present a passive monitoring and tracking solution for effective and relevant personalized feedback and decision support[4].

The Dem@Care solution offers a unified framework with knowledge representation for sensor interoperability that measures multiple aspects of health, context and lifestyle to automatically assess disturbances and their causes, aiding clinical monitoring and interventions for the provision of personalized care recommendations.

3. THE DEM@CARE FRAMEWORK

The central goal of Dem@Care is to help individuals with dementia live independently alone for as long as possible, by monitoring aspects of their life considered to be most important by clinical experts (in this case sleeping, eating, sociability, levels of activity, mood). The sensors used are unobtrusive and can provide useful data on these five areas after appropriate analysis and intelligent fusion, as many of them provide indirect information on the aspects of a person's daily life. It should also be noted that the system is modular, as some of the sensing modalities cannot be used in all environments or countries, depending on the corresponding ethical regulations.

[1]Home sensing solutions inlucde: https://www.smartthings.com/, http://www.awarehome.gatech.edu/

[2]http://www.doc.ic.ac.uk/vip/ubisense

[3]Robotic AAL: http://www.radio-project.eu/, http://accompanyproject.eu/,http://giraffplus.eu/

[4]The Dem@Care FP7 project - www.demcare.eu

3.1 Dem@Care sensors

The sensing modalities deployed aim to monitor the environment (temperature, motion/presence, electricity consumption etc), the health status of the individual (via wearable fitness trackers, sleep monitors, recognition of daily activities from video, speech analysis), either by ambient sensors placed in the house, or wearables. The sensors used are proprietary low-cost devices (Fig. 1), and include motion sensors, a wearable fitness tracker, a sleep monitor, motion sensors, audio, video and smart plugs. A subset of these sensors is used in each deployment, depending on the environment (e.g. in a home or in a hospital), each individual's needs and national and international ethical/legal regulations.

Ambient motion sensors monitor entrace/exit from rooms, giving a picture of a person's levels of activity, presence in certain rooms, the presence of others (to detect levels of sociability), and also providing added security, since they can indicate the presence of an intruder. Object motion sensors, known as tags, are also used to detect the movements of objects (e.g. coffeemaker) and determine they are being used. Smart plugs track the usage of devices related to daily activities (e.g. refrigerator, TV, coffee maker), giving a clear picture of an individual's habits and lifestyle over time.

Health status can be inferred from wearable fitness trackers' and ambient sleep trackers' measurements, while changes in their outputs over a long period of time can serve as valuable early signs of improvement or worsening of a person's condition. In clinical interview style setups, wearable microphones are used to detect potential early signs of dementia or deterioration from the analysis of a person's speech. Video obtained from ambient color or color-depth cameras is used to monitor a person's lifestyle, with a focus on the detection activities of daily living (ADLs) necessary for independent living, as dictated by clinical experts. Cameras also serve security purposes, to prevent or record criminal activity in the house, such as a robbery, or even help prevent abuse that could take place in a nursing home.

3.2 Sensor framework and data analysis

The multimodal sensor framework of Dem@Care is realized using the architecture depicted in Fig. 1, with the following layers: (1) sensors layer comprising of all sensors and their measurements, (2) analysis layer, for the analysis of the sensor measurements (3) representation layer, for a unanimous semantic representation (4) interpretation layer for the semantic interpretation and fusion, (5) service layer, corresponding to the web service interface and (6) application layer, with domain-specific end-user applications.

The measurement data undergoes different types of analysis, depending on the sensors. Simpler sensors, e.g. for physiological monitoring, are processed and interpreted according to open data formats or using proprietary libraries, which result in a directly interpretable outcome. Longer term monitoring outcomes, e.g. from smartplugs, can be aggregated over time to detect consumption and lifestyle patterns. Other sensor data, namely audio and video, requires the development and use of sophisticated statistical and machine learning algorithms for their analysis and the extraction of higher level information. The ability to live independently alone depends on a person's ability to carry out activities of daily living (ADLs), which are dictated by clinicians. These are detected in videos using State of the

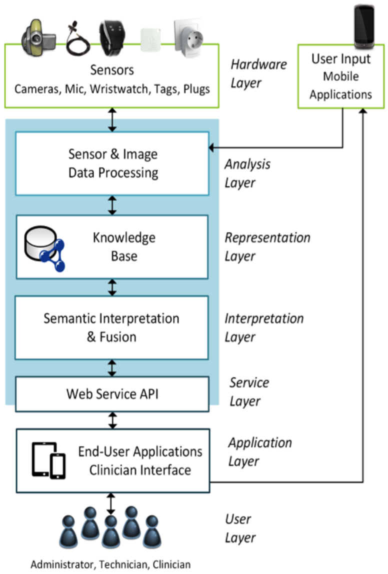

Figure 1: Dem@Care framework: sensors, analysis modules, applications

Art (SoA) computer vision algorithms [1], [2], resulting in indicators of difficulties in daily life, related to dementia. In particular, people with cognitive difficulties carry out ADLs more slowly, or after many repetitions: this information can only be obtained from video, where specific ADLs can be detected. It should be noted that video is only deployed in environments where it is allowed, following the current ethical and legal regulations in each country, and always after informed consent is obtained. Testing takes place in different environments, ranging from constrained hospital lab environments, where individuals are asked to carry out specific ADLs (Fig. 2), to home monitoring. Most importantly, to ensure privacy, raw video data is not stored or transmitted, but is either analyzed online, or in each location of deployment. Furthermore, only non-identifying encrypted metadata is transmitted over secure networks. Finally, in some setups (mostly in hospital environments) audio recordings of the individual performing specific speech exercises were analyzed in the spectral domain. Changes in a person's speech, or even certain characteristics (e.g. speaking more slowly, with many pauses, slurring etc) were shown to be correlated to their cognitive status and its evolution, providing insights about early indicators of dementia that cannot be obtained from other modalities.

3.3 Semantic Fusion and Integration

Intelligent fusion of the sensor analysis outcomes takes place by first developing a Knowledge Base (KB) that models domain knowledge. The domain knowledge in this case concerns clinical aspects, as well as aspects of the person's daily life and profile, such as demographics and clinical history. Measurements and activities are also represented, including their location, objects and temporal context. In real-world applications, activities can appear as a complex combination of measurement data. This is handled by the design of activity ontologies to represent relations between sensor outputs, context, activities, and their classification.

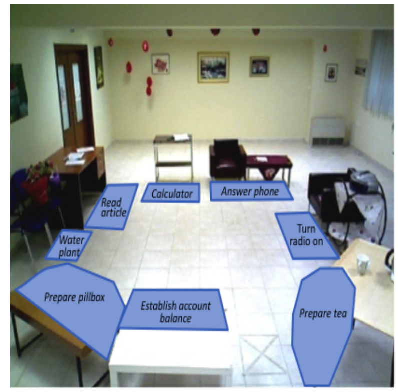

Figure 2: Activity Zones

High-level activity recognition is realized in the Semantic Interpretation (SI) layer, where the intelligent fusion of simpler activities takes place, leading to a more accurate profile of the person being monitored. SI implements a location-driven context generation and classification approach. Each room is divided into zones, according to the location of each activity, so wjen a participant enters a zone, the SI generates a container instance and starts associating it with collected observations related to that zone. These container instances actually capture contextual information and are used to recognize ongoing activities. Temporal aspects of the measurements and activities being detected are also taken into account, as they can help further discriminate between different ADLs. Within Dem@Care, the temporal intervals of the activities taking place are extracted from the sensor data, thus providing temporal context.

4. DEPLOYMENT AND EVALUATION

The proposed health monitoring and feedback framework is deployed in several different environments to demonstrate its capabilities and assess its usability in real-world applications. The modular nature of the system allows different subsets of its components to be deployed in each setup, depending on user needs, trial protocols and so on.

4.1 Lab Deployment

Lab-type deployments usually involve a protocol of ADLs to be carried out by the individual over a short time period (about 20 minutes), monitored by the proposed system. The results are directly communicated to the end users, i.e. doctors and nurses, giving them a richer and objective picture of the individual. These tests allow for the use of a larger number of sensors, since their duration is short and they do not concern a person's private life. The setup in Fig. 3 contains object motion sensors, to measure object usage, and a smartplug for the teakettle. Ambient video cameras record the entire scene, so as to monitor the activities carried out by the subject and detect how they take place.

The lab implementation results are communicated to end users by a graphical user interface, which has been designed to (1) assess the individual's health status and ability to carry out daily activities, (2) view the outcomes of the sensor measurements and analysis in an understandable manner. The assessment screen can be seen in Fig. 4, where an instantiation before the testing is shown: in this case, the

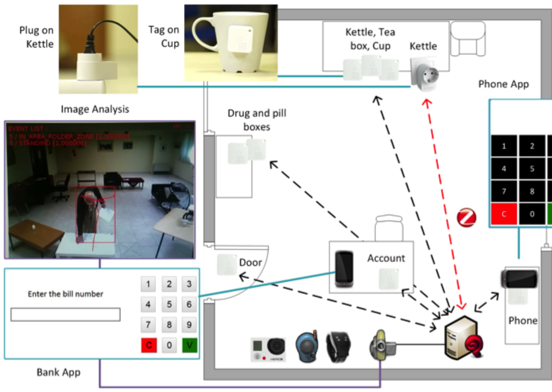

Figure 3: Sensor setup and deployment in the lab

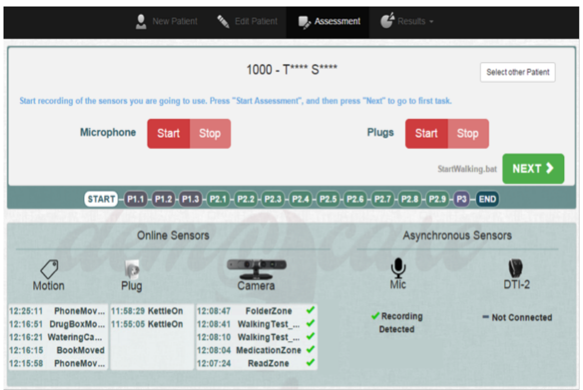

Figure 4: Sensor initialization screen for lab setup

users can check the status and activate/deactivate sensors, according to the current protocol step (upper part) while monitoring sensor events and connectivity in real-time (bottom part).

A timeline of both complete and incomplete activities, highlighted in green and red respectively, is also shown, along with further details for the activities, such as their relative order, total duration and number of repetitions, which can all provide valuable insights to clinicians.

4.1.1 Results from Lab Clinical Trials

In a hospital environment deployment with 98 participants (27 Alzheimer's Disease - AD, 38 Mild Cognitive Impairment - MCI, 33 Healthy), aged 60-90, it was shown that the system can successfully conduct lab trials autonomously, allowing psychologists and other caregivers (nurses, neurologists and other clinicians) to examine a larger number of individuals in an objective and reliable manner. Their feedback on the usability of the interfaces and the system in general was very positive and participation in the pilots was high.

Initial assessments of individuals and new insights on their conditions have already been obtained from these first trails, as a statistically significant difference was found in the duration and the number of attempts carried out for ADLs between people with dementia and healthy individuals. MCI participants completed the phone call and the account payment activities, while individuals with AD could not, allowing the system to distinguish them with a mean accuracy of

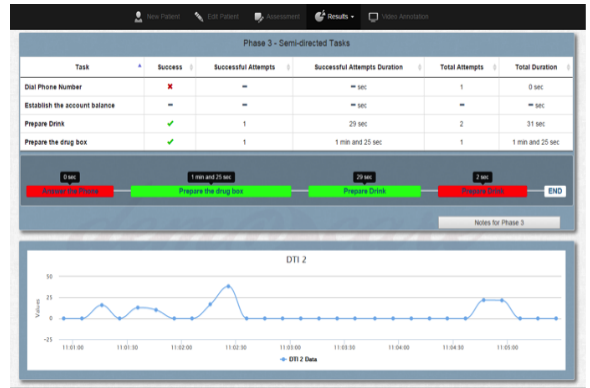

Figure 5: Lab results screen after testing

73.67%. Similarly, individuals with MCI were able to pay a bank bill and make a phone call, allowing the system to distinguish between them with 84% accuracy.

4.2 Home Deployment

Home deployments differ from lab tests as they involve continuous testing, aiming to support the individuals in their daily life, while ethical regulations limit the sensors that can be used in each country. The monitoring results are fused in an intelligent manner, as before, and communicated to the end users to support diagnosis, evaluation, care options and provide personalized feedback to the patient. Fig. 6 provides a comprehensive overview of the Dem@Care system deployed in homes, called Dem@Home. It shows the minimum set of devices used in homes, after confirming that they a) fulfill acceptability requirements for the home residents and b) the quality and quantity of symptom-related information they provide fulfills the clinical monitoring requirements as set by psychologists. In detail, all devices are ambient, except a light wearable wristband, and are installed transparently in the home user's environment. The wristband, is barely noticeable, and is found to provide a feeling of safety and inclusion while being monitored. In this manner, the Dem@Care setup provides an unobtrusive comprehensive monitoring solution that results in an accurate and in depth picture of the person's lifestyle and health status.

4.2.1 Results from Home Pilots

Pilots also took place at home (Fig. 7), with four users with MCI and mild dementia, who indeed benefited from the deployment of the system. The system interface allowed the identification of difficulties in daily living, such as many sleep interruptions, neglect of daily tasks like cleaning and decreased levels of activity.

The caregivers provided the appropriate feedback for each issue and continued monitoring their progress in that domain. They encouraged the patients to walk more and monitored them through their wrist-worn fitness tracker. To monitor daily chores, daily activity recognition modules were deployed via smartplugs, object motion trackers on devices (vacuum cleaner, iron etc), and via computer vision based detection of ADLs [2]. ADL recognition allowed the clinician to monitor the individuals' daily activities throughout the entire day, and determine that they were adhering to the suggested interventions and also showing some improve-

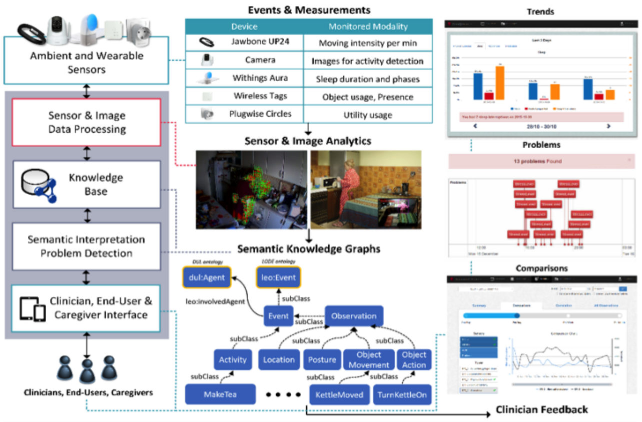

Figure 6: Dem@Home architecture and information flow in home deployments

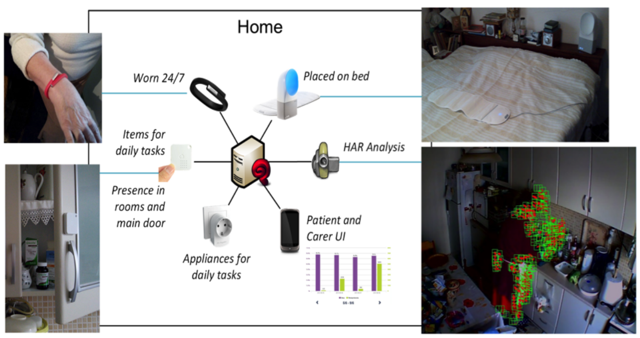

Figure 7: Dem@Home sensor setup

ments. Overall, after monitoring four users for a period of at least two months each, the system monitoring outcomes and weekly interviews confirmed that the participants showed an increase in physical activity, improved sleep and mood.

5. CONCLUSIONS

A comprehensive solution for multimodal monitoring, intelligent fusion and personalized decision support for remote care, focusing on the case of dementia, has been presented. Numerous heterogeneous sensing modalities have been seamlessly integrated, combining ambient, wearable and lifestyle sensors. A set of processing components ranging from sensor analytics for event detection to sophisticated image, video and audio analytics, was integrated and analyzed. All knowledge is unanimously stored in a knowledge base, enabling its semantic interpretation for further fusion, aggregation and detection of problematic behaviours. The framework was designed for monitoring people with dementia after consulting clinical experts on user requirements, monitoring and feedback. Real world testing in lab and home environments led to improvements in the health status of individuals living at home and accurate assessments in the lab, thanks to the reliable monitoring and tailored feedback.

Future directions from this work include the extension of both the framework and its clinical applications. The system can be extended to a complete solution for real-time feedback, while mood and stress can also be assessed via the latest wearable sensors, especially in home settings. While the framework has been deployed in numerous locations, it can yet be extended for increased portability and installability. Combined with the infrastructure to push the events on a cloud infrastructure, the framework could constitute a powerful platform for telemedicine and mobile health, combing sensors and sophisticated ambient intelligence techniques such as computer vision.

6. ACKNOWLEDGMENTS

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